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# THE PERFORMANCE OF CARBON FIBRE REINFORCED POLYMER STRENGTHENING DURING A REAL FIRE

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## ABSTRACT

Fibre reinforced polymer (FRP) strengthening methods can be used to repair or upgrade deficient structures and are increasingly adopted for the ease with which they can be applied. For example, the strength of a concrete floor slab can be increased by bonding a preformed carbon fibre plate to its underside. The FRP strengthening, however, is critically dependent upon the bonding adhesive. The adhesive used is typically an ambient cure epoxy with a glass transition temperature of as low as 60°C. This paper describes the performance of bonded FRP strengthening within 'real' fires. The opportunity was taken to include FRP strengthening within compartment fire tests, one of which was allowed to grow past flash-over (the Dalmarnock Fire Tests). Plate and near surface mounted types of FRP strengthening were applied to the ceiling of the cast in-situ concrete structure. Intumescent and gypsum board fire protection were applied, together with FRP that was left unprotected. During the fire tests, temperatures and strains were recorded within the adhesive layer and within the concrete slab. The aim of these tests was to demonstrate the performance of FRP strengthening during a real fire, which compliments the laboratory-based fire tests on FRP strengthened members that are currently being undertaken at a variety of research centres. The analysis of this data has still to be completed, due to the complexity of the non-uniform temperatures and strains developed in the fire compartment; however, the tests demonstrated the vulnerability of FRP strengthening within a real compartment fire. They also demonstrated that NSM strengthening has superior integrity to plate strengthening during a fire, and that gypsum board fire protection can be used to reduce the temperature of the adhesive, and hence preserve the integrity of the FRP strengthening.

## INTRODUCTION

Buildings are refurbished many times during their lives, often requiring structural alterations to the building form, or strengthening works. Building owners naturally look for the most economic refurbishment scheme, and this cost is dominated by the disruption to the building's normal use. Bonded fibre-reinforced-polymer (FRP) strengthening is an increasingly popular method for refurbishment. This involves gluing an advanced fibre composite on to the existing structure to increase its sectional capacity. Although commonly described as 'strengthening', it has a variety of other uses, such as to reduce deflections. Where holes need to be cut in a concrete slab (for example, to insert services, a lift shaft, or a light well), FRP can be bonded around the perimeter of the hole before it is cut so as to carry the increased stress resultants. The lightweight and non-corrosive properties of the FRP are advantageous, but it is the consequential savings in installation time and equipment that have helped FRP strengthening become a mainstream structural refurbishment technique.

One issue that has yet to be fully addressed is the fire performance of bonded FRP strengthening [1]. In July 2006, the BRE Centre for Fire Safety Engineering at the University of Edinburgh conducted fire tests in a cast in-situ concrete building in Dalmarnock, Glasgow [2], which included two full-scale compartment fires. Test 1 was allowed to grow to post flash-over, whereas the ventilation in Test 2 was controlled to prevent flash-over being reached. The opportunity was taken to evaluate the performance of bonded FRP during the Dalmarnock fire tests.

## BONDED FRP STRENGTHENING IN FIRE

Bonded FRP strengthening involves four materials:

- the fibres that reinforce the FRP component (commonly carbon fibre);
- the matrix polymer that forms the FRP component (often an epoxy resin);

- the bonding adhesive (usually epoxy); and
- the substrate (in this case, concrete).

The most critical of these materials in fire is the *bonding adhesive*. A 2-part, ambient-cure, epoxy adhesive is usually used to bond the FRP to the substrate, with a glass transition temperature that is in the range 60°C to 85°C [3]; i.e. well below the temperatures expected in a compartment fire. Other bonding adhesives have higher glass transition temperatures, but require elevated temperature curing that is difficult on a large structure. For convenience, the FRP component can be preformed off-site and can consequently be autoclaved. This gives the matrix polymer a higher glass transition temperature, but the on-site bonding operation requires an ambient cure adhesive. Where the FRP is formed in-situ, however, the matrix polymer and bonding adhesive are the same.

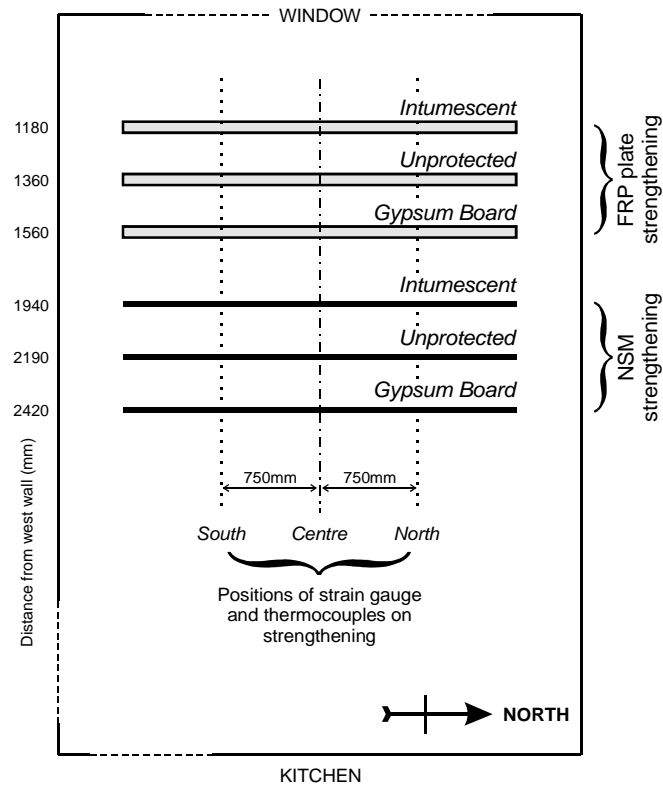
Current practice recognises that the low glass transition temperature of the bonding adhesive is a concern. For example, UK design guidance states that “*Unless a rigorous analysis is undertaken it is sensible to neglect the strengthening from FRP in fire situations*” [4]. Neglecting the FRP strengthening may be acceptable if the FRP is not needed for the structure to carry the loads that are present during a fire scenario (which are lower than the ultimate load for which the strengthening is designed). However, where FRP strengthening is designed to carry permanent loads, the strengthening might be required during a fire. This may occur, for example, where the dead load is increased by high density filing systems or library shelves, or where FRP is used to carry the perimeter stresses around a new hole cut into a concrete slab to insert services (an increasingly common application). If the strengthening is required during a fire, the bonding adhesive must be insulated using a suitable protection system. Current guidance highlights the lack of knowledge on suitable protection systems: “*Regulations may require the application of an over-coat layer, which has been tested on the fully-cured composite system*” [4]. This is impractical for the design engineer who is working to a limited budget and timescale, and may be tempted to use ‘engineering judgement’ to adapt traditional insulation methods such as an intumescent coating or gypsum board insulation.

Recent research has started to address fire protection for bonded FRP. Furnace tests were carried out by Blondtrock *et al.* [5] using combinations of gypsum board and mineral wool insulation. Barnes and Fidell [6] report tests that used a proprietary cementitious fire protection, and supplemented the bonding adhesive with bolted fastenings. Proprietary systems have been specifically developed to protect bonded FRP strengthening and these have been tested applied to columns and slabs [3]. All previously reported tests have been carried out using a furnace, using a prescribed time-temperature curve that is quite different to reality [7]. The bonded FRP fire tests carried out in Dalmarnock are unique, as they involved ‘real’ fires.

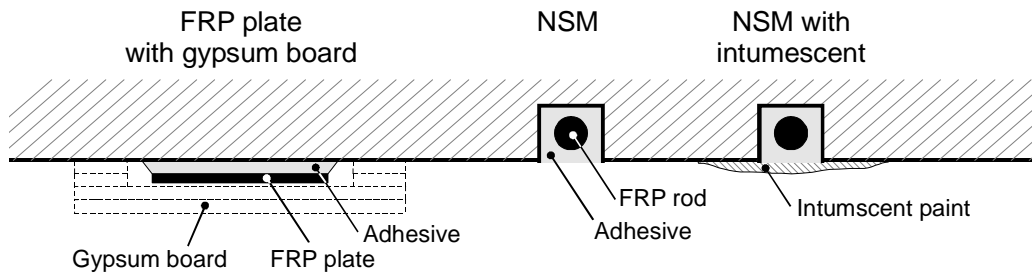
## DESCRIPTION OF THE TEST ARRANGEMENT

The fire tests took place in the living rooms of two flats, part of a 23-storey residential building that was built in 1964. The fire compartment and furnishings were identical in the uncontrolled (Test 1) and controlled (Test 2) fires, except for the ventilation. The compartment layout is shown indicatively in figure 1. The fire load consisted of office furnishings, and was dominated by a sofa placed towards the rear of the compartment. In the uncontrolled test, the compartment was ventilated by an open door to the rest of the flat and the openings left by breaking windows during the later stages of the fire; in the controlled test the ventilation parameters were changed by remote control of the windows and door [8].

Two types of bonded FRP strengthening were installed in the Dalmarnock test: Plate and Near-Surface-Mounted (NSM), shown schematically in Figure 2. Plate strengthening requires any loose material to be removed from the surface of the concrete to expose a sound substrate, to which the pre-formed plate is bonded. For NSM strengthening, a groove is cut into the concrete; a bar of FRP is bonded into the groove; and the groove is filled flush with adhesive.



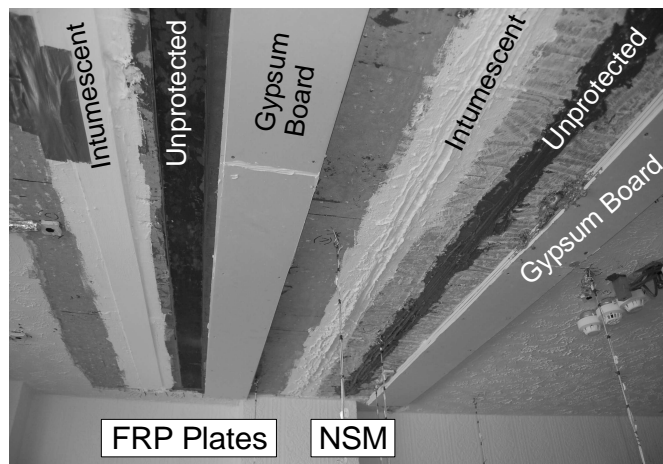
**Figure 1: Plan view of the strengthening and instrumentation**



**Figure 2: Types of FRP strengthening and protection (schematic)**



(a) Compartment, with FRP at top



(b) The six strips of strengthening

**Figure 3: The installed FRP strengthening and protection**



Six strips of strengthening were installed in the compartment used in Test 1: three using plates and three NSM (Figures 1 and 3). One of each type of strengthening was left unprotected, one painted with an intumescent coating, and one was protected within a gypsum board box. The gypsum board protection comprised two layers of 12mm board, spaced away from the bottom of the slab by a further two layers of board, placed to either side of the strengthening (Figure 1). The joints were staggered and the layers were sealed with an intumescent sealant. The strengthening was installed by a contractor skilled in the application of bonded FRP (figure 4), and was completed 20 days before the fire test. The fire protection systems were installed by the University of Edinburgh. A single unprotected plate and unprotected NSM bar were installed in Test 2.



**Figure 4: Installing a strengthening plate**

<b>Bonding adhesive</b>	<i>Two component epoxy based adhesive</i>	
	Mechanical properties:	$E = 10 \text{ GPa}$ ; Lap shear strength = 17 MPa
	Cure time:	Fully cured in 7 days
	Glass transition temperature:	$\geq 65^{\circ}\text{C}$
<b>FRP plate</b>	<i>Pultruded MM (medium modulus) CFRP plate with epoxy matrix</i>	
	Dimensions:	100 x 1.4mm
	Mechanical properties:	Tensile modulus = 170 GPa; Tensile strength = 3100 MPa
	Coefficient of linear thermal expansion:	$0.6 \times 10^{-6} / ^{\circ}\text{C}$
<b>FRP NSM rod</b>	<i>Pultruded CFRP rod with epoxy matrix</i>	
	Dimensions:	12mm diameter
	Mechanical properties:	Tensile modulus = 165 GPa; Tensile strength = 2500 MPa
	Coefficient of linear thermal expansion:	$0.6 \times 10^{-6} / ^{\circ}\text{C}$
<b>Intumescent paint</b>	<i>Thin film water borne intumescent coating</i>	
	Application:	2 coats by brush, estimated thickness 450 $\mu\text{m}$
	Activation temperature	120 $^{\circ}\text{C}$ , from tests on the same material in [9].

**Table 1: The FRP and protection materials  
(Manufacturer's data sheet values)**

Table 1 gives the pertinent properties of the materials used in the Dalmarnock tests. Note in particular that the glass transition temperature of the bonding adhesive is given as ' $\geq 65^{\circ}\text{C}$ '. This is the manufacturer's quoted value, and is rather unsatisfactory. The authors intend carrying out further tests on the adhesive to determine the actual glass transition temperature.

Intumescent coatings are intended for protecting steel members, not FRP. Their activation temperature is usually higher than the glass transition temperature of the adhesive. However, the authors are aware of intumescent protection being *specified* for a bonded FRP project by design engineers (although this was changed before *implementation*). The opportunity was therefore taken to demonstrate the performance of the intumescent protection during the Dalmarnock tests.

Before installation, the FRP components in Test 1 were instrumented with strain gauges (attached to the upper surface of the FRP at the North, Centre and South positions shown in Figure 2), and thermocouples (placed within the adhesive layer at the same positions). The wires were led up through the concrete slab, with any holes filled with intumescent foam. Further instrumentation was used to monitor the structural response of the slab [10], and to record the progress of the fire [8].

## RESULTS AND OBSERVATIONS

The condition of the bonded strengthening after the uncontrolled fire (Test 1) is shown in Figure 5:

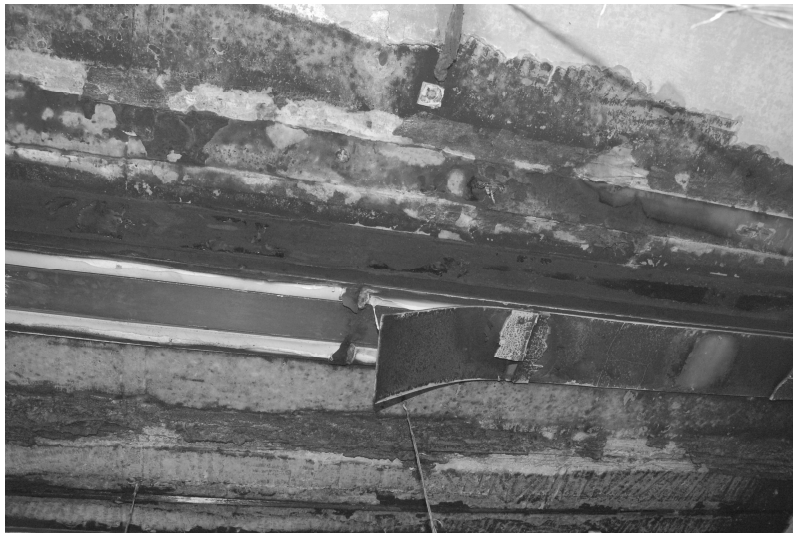
- The unprotected plate (figure 5a) had completely separated from the concrete. Both the bonding adhesive and the matrix polymer had burnt away, leaving exposed concrete on the ceiling and the fibres exposed on the floor.
- The intumescent protected plate (figure 5b) separated from the concrete, except for a short length at its southern end, where it remained bonded to the concrete. Away from this end, the matrix polymer had burnt away to expose the fibres. The bonding adhesive was charred, but remained on the ceiling.
- The gypsum-board protection was inspected after the tests, and was fully intact. When the board was removed (Figure 5c), the plate was fully bonded to the concrete, and there was no *visual* damage to either the plate or adhesive.
- The adhesive around the unprotected NSM bar (figure 5d) had burnt away, leaving the FRP exposed.
- The intumescent coating over NSM strengthening (figure 5d) had activated. The strengthening beneath the intumescent was in place, although the adhesive was glazed and contained transverse cracks.
- The gypsum-board protected NSM (figure 5d) remained intact, and the strengthening beneath was visually unaltered.



**Figure 5a: Remains of unprotected plate**



**Figure 5b: Remains of intumescent-protected plate**



**Figure 5c: Gypsum-board-protected plate  
(protection removed after fire to expose plate)**



**Figure 5d: NSM strengthening after the fire.**

The uncontrolled fire produced a peak heat release rate of 800kW. Figure 6 includes gas phase temperatures recorded from a single thermocouple near the ceiling slab in the centre of the strengthened region, but it should be noted that the temperatures varied across the compartment. The figure also indicates the major fire events: notably a growth period, ending with flashover at 5 minutes; and the fire was extinguished at 19 minutes. Further information on the fire growth is given in [11].

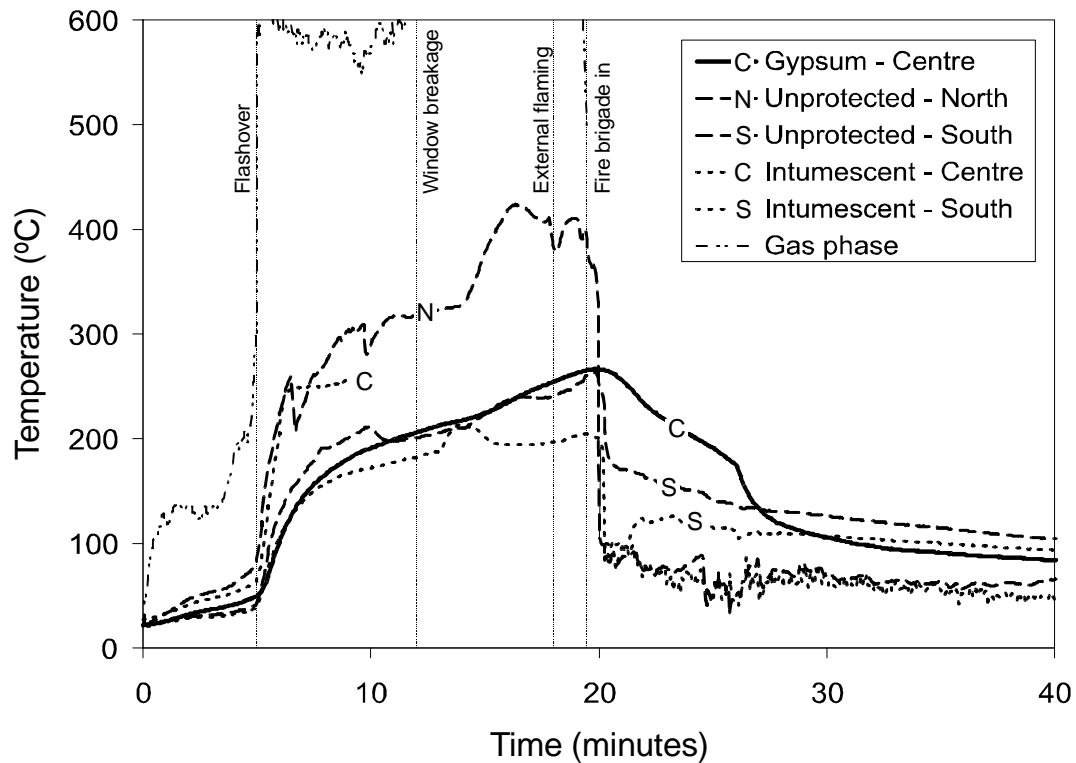


Figure 6a: Bondline temperatures - plates

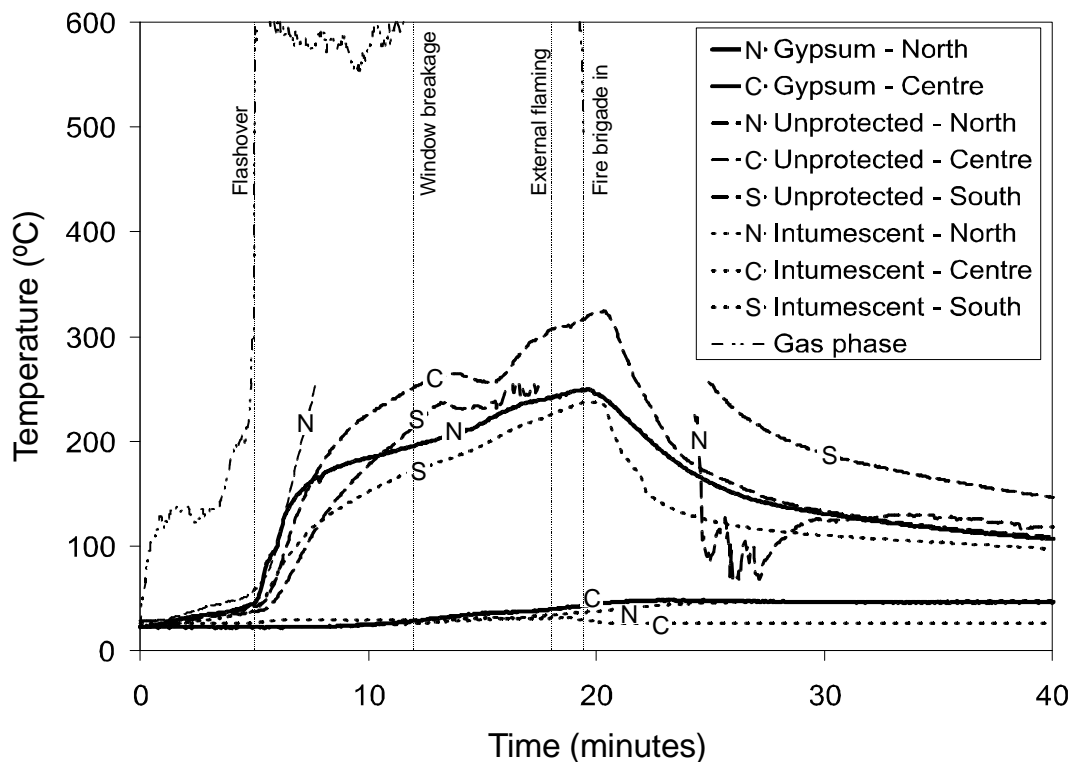


Figure 6b: Bondline temperatures - NSM

Figure 6 also shows the temperatures recorded by the bondline thermocouples, for each strengthening type and at each position (north, centre and south). There were a few inactive thermocouples (not shown), and the readings for 3 thermocouples (gypsum-centre, intumescent-north and intumescent-centre) are erroneous. Note that some of the readings in Figure 6 were taken after a plate had separated from the ceiling. In all cases the bondline temperature was well above the glass transition temperature of the adhesive. As expected, the bondline temperatures are highest in the unprotected plates; however, even with gypsum-board protection, the glass transition temperature was reached within a minute after flash-over. This was much more rapid than previous furnace-based research (eg: [5]). Although the protection is not directly comparable, these furnace-based tests suggest that it takes in the order of 20 minutes for a similar temperature rise. Without further analysis it is not possible to draw comparisons between the plate and NSM temperatures.

Figure 7 shows the strain gauge results, presented here before correction for temperature effects. These strain results are all due to thermal effects: (a) thermal expansion of the FRP component, possibly in composite action with the concrete, (b) differential thermal expansion between the gauge and the FRP, and (c) apparent strains due to electrical effects in the gauge. Future work will use thermocouple readings adjacent to the strain gauges to remove components (b) and (c), but this has not yet been carried out with sufficient rigour to present the results here. It is important to note that the strain gauges and gauge adhesive were only intended for use up to 200°C, consequently the correction will not be accurate and there may have been slip in the gauge adhesive above this temperature. Also, the time resolution of the data is poor, and the negative strains for the intumescent-protected NSM are anomalous.

Nevertheless, the uncorrected strain evolutions in Figure 7 are useful. Separation of the intumescent plate from the concrete, for example, occurred about 10 minutes from the start of the test, but the plate remained in contact at the southern end (confirmed by Figure 5b). The gypsum board protected strengthening have complete strain traces. The negative strains for the north gypsum-protected NSM gauge suggest the FRP has slipped relative to the concrete slab due to adhesive viscosity at high temperatures, but solidified during cooling. Further work, however, is required to analyse these results.

In the controlled fire (Test 2), gas-phase temperatures were significantly lower than during Test 1, and the fire was extinguished before flash-over was allowed to occur. Further details of the fire growth can be found in [12]. The unprotected FRP plate and NSM strengthening were *visually* unaffected by the fire: the colour had not changed, there was no sign of crazing of the adhesive, and the strengthening remained in place. (The test 2 strengthening was not instrumented).

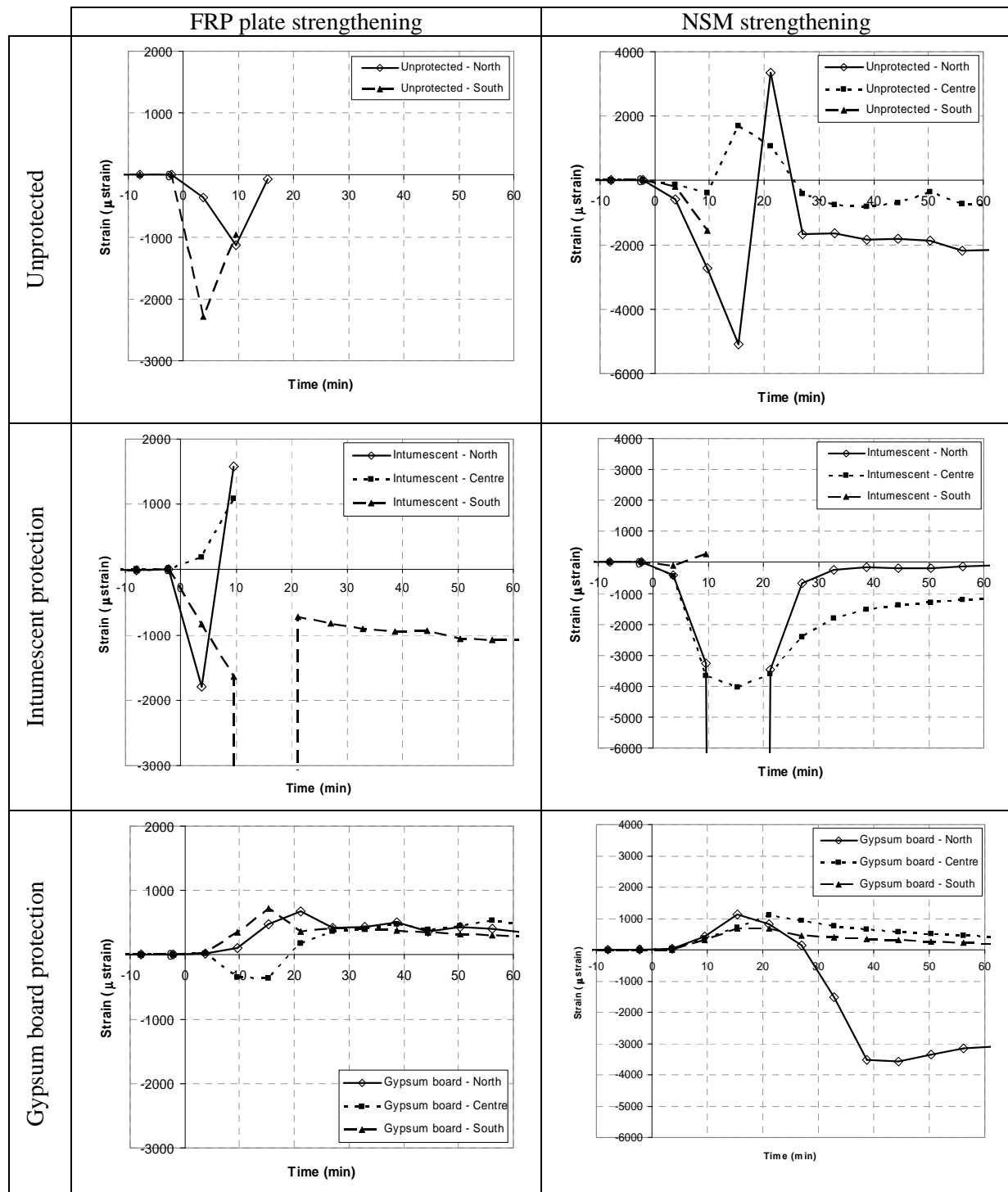
## ONGOING WORK

The interpretation of test results described herein is limited by the need for further work, which is being carried out in parallel to analysis of the structural data [10]. This includes correlation of slab strain with the FRP strain, consideration of local variations in gas phase temperature, and determination of the time of separation events. Materials characterisation will be undertaken, and a thermal analysis of the protected strengthening carried out.

## CONCLUSIONS

The bonded FRP strengthening installed in Dalmarnock Test 1 are the first in a ‘real’, flash-over fire. The results and preliminary analysis have demonstrated the vulnerability of the bonding adhesive during a fire; the bondline temperature greatly exceeded the glass transition temperature in all tests (with and without protection). Furthermore, this temperature was reached far more quickly than furnace-based testing has suggested.

NSM strengthening has superior integrity to plate strengthening during a fire. The surrounding concrete would be expected to draw heat away from the adhesive, but further analysis of the test data is required to investigate this.



**Figure 7: Uncorrected FRP strain measurements**

The intumescent protection was ineffective, due to an activation temperature that exceeded the glass transition temperature of the adhesive. The plate strengthening separated from the concrete, and there was visible damage to the NSM bonding adhesive.

Where the adhesive or matrix polymers were exposed to the fire, they burnt or charred, and would have released toxic fumes. This occurred in the unprotected tests, and due to separation of the intumescent-protected plate from the concrete.

The gypsum board protected the FRP strengthening from visible damage. However, the strengthening would not have been mechanically active during the test, due to the glass transition temperature having been exceeded.

## ACKNOWLEDGEMENTS

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